AD-A173 974 A FRAMEWORK FOR AN OPTIMUM SYNTHESIS ENVIRONMENT FOR THE HYDROCODE EPIC-2(U) AIR FORCE ARMAMENT LAB EGLIN AFB FL P HAJELA OCT 86 AFATL-TR-86-60 SBI-AD-E801 395 1/1

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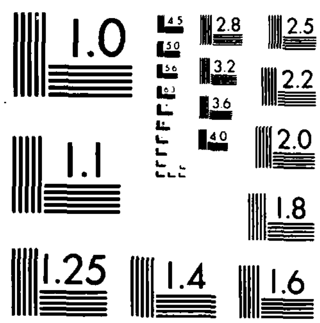

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A Framework for an Optimum Synthesis Environment for the Hydrocode EPIC-2

Prabhat Hajela

CLUSTERS AND WARHEADS BRANCH
MUNITIONS DIVISION

AD-A173 974

OCTOBER 1986

FINAL REPORT FOR PERIOD MAY 1986-JULY 1986

AIR FORCE ARMAMENT LABORATORY
Air Force Systems Command ▪ United States Air Force ▪ Eglin Air Force Base, Florida

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FOR THE COMMANDER

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AD-A173974

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for Public Release; Distribution Unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFATL-TR-86-60

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: Munitions Division

6b. OFFICE SYMBOL (If applicable): MNW

7a. NAME OF MONITORING ORGANIZATION: AFOSR

6c. ADDRESS (City, State, and ZIP Code): AFATL/MNW, Eglin AFB, FL 32542-5434

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: AFOSR

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F49620-85-C-0013 (6.1 funds)

8c. ADDRESS (City, State, and ZIP Code): Eglin AFB, FL 32542-5000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): A Framework for an Optimum Synthesis Environment for the Hydrocode EPIC-2 (U)

12. PERSONAL AUTHOR(S): Prabhat Hajela

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 1 May 86 TO 12 Jul 86

14. DATE OF REPORT (Year, Month, Day): October 1986

15. PAGE COUNT: 38

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
12	01	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Optimal Design, EPIC-2, Structural Design, Impact, CONOPT

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The present study seeks to examine the efficacy of a mathematical nonlinear programming approach for the optimal synthesis of structures subjected to high strain-rate plastic deformations. Efficient methods of constraint representation are implemented to reduce the dimensionality of the optimization problem, where the latter is an outcome of the transient nature of the response functions. A Lagrangian discretized domain approach is used for the solution of the equations of motion and is coupled to a feasible usable search direction algorithm to form an optimization programming system. The optimum sizing of a projectile shell for survival in a high velocity impact, provides the test problem for this study. A stepwise linearization of the design space is attempted for computational efficiency, with encouraging results.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Mike Nixon

22b. TELEPHONE (Include Area Code): 904-882-2145

22c. OFFICE SYMBOL: AFATL/MNW

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

PREFACE

This report describes work performed by Professor P. Hajela of the University of Florida, under the Air Force Office of Scientific Research (AFOSR) Summer Faculty Research Program, Contract no. F49620-85-C-0013. The research was conducted at the Air Force Armament Laboratory (AFATL), Clusters and Warheads Branch (MNW), Eglin AFB, Florida during the period May 1, 1986 through July 12, 1986.

The author would like to acknowledge the support of the Air Force Systems Command and the AFOSR for their support of this effort. The author would also like to thank AFATL for extending the use of their research facilities. The invaluable assistance from Mr. M. E. Nixon and Lt. D. L. May is gratefully acknowledged. Discussions with Messrs M. E. Gunger and W. H. Cook were extremely useful in identifying pertinent characteristics of the problem examined in this study.

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SECTION I
INTRODUCTION

Significant advances in digital computing capabilities, coupled with parallel development of more efficient methods of analysis, have contributed to the emergence of automated structural synthesis as a viable design tool. Early contributions to the concept of optimum structural design can be found in publications of Maxwell (Reference 1) and Michell (Reference 2). The 1950's witnessed the development of the simultaneous failure mode theory (Reference 3), in which a structure was considered optimal if it failed in each of the several failure modes at the same load condition. The contemporary approach to the optimum structural synthesis problem can be traced to the pioneering efforts of Schmit (Reference 4). The past two decades have witnessed considerable research activity in the field and has resulted in the emergence of two distinct approaches - the optimality criteria methods (Reference 5) and the nonlinear programming technique (Reference 6). An extensive review of the literature in this period is documented in Reference 7 . Of the optimality criteria and the nonlinear programming strategies, the latter is considered a more general approach, and is used in the work described in this report.

The nonlinear programming approach has enjoyed considerable success in the design of elastic structural systems subjected to static load conditions. The methodology involves the coupling of a mathematical nonlinear programming algorithm to an analysis procedure for a given problem domain, in order to obtain an optimization programming system (Reference 8). Despite the apparent success of this approach, there are several drawbacks that must be considered in its implementation. Strictly speaking, the problem of optimal structural synthesis is one of repetitive analysis of candidate designs, to obtain the best in terms of a prescribed set of conditions. Rather than use a random selection of the trial designs, the optimization algorithm provides a systematic search procedure. Furthermore, the search for new designs is terminated when certain mathematically determined conditions for optimality, such as the Kuhn-Tucker conditions (Reference 9), are satisfied. The search techniques for constrained optimization problems need the gradients of the constraints and the objective function, in addition to the function values.

Hence, in the presence of a large number of design variables and constraints, such methods become extremely inefficient from a computational standpoint.

Several approaches have been suggested to circumvent the problems of large dimensionality described above. One approach to reduce the computer resource requirements is to substitute the detailed analysis of the structure by an approximate analysis of a reduced order model. Such methods have been proposed and implemented with a great degree of success. The other approach is to simplify the design space itself by reducing the number of design variables and constraints that the optimization algorithm has to contend with. Design variable linking is a process that allows the user to limit the number of design variables in the optimization. Constraint deletion and cumulative constraint representations permit a further reduction in the dimensionality of the design space. Additional savings in computational effort can be achieved by constructing high quality explicit approximations to the design space. A detailed description of these concepts is available in References 10, 11,and 12 .

The developments described above have been largely confined to the design of statically loaded, elastic structural systems. Constraints obtained from a dynamic loading environment have largely been of the form in which the natural frequencies of the structure are constrained to lie in some prespecified pockets (Reference 13). Transient response constraints (Reference 14) and constraints from a random loading environment (Reference 15) have received little attention in this effort. Also included in the latter category is the optimum design of structures which exhibit geometric or material nonlinearities.

The primary focus of the work described in this effort was to assess the applicability of optimization methods in the design of structures that undergo significant plastic deformations under dynamic loads. This includes the development of an optimization programming system for the task. An additional task was to identify the problem areas typical of this class of structures, where the analysis is inherently nonlinear and does not lend itself conveniently to the approximation concepts developed in context of optimum design of elastic systems. The test problem chosen for this task was a shell colliding against a rigid wall with a prescribed velocity, resulting in severe plastic deformations in the structure. An interesting feature of the proposed problem

is its resemblance to a shape optimization problem, a subject that has received considerable recent attention (References 16 and 17). Subsequent sections of this report describe the structural optimization problem, the implementation of the cumulative constraint concept to circumvent the parametric nature of the design constraints, the description of the optimization programming system, and preliminary results for the test problem. Shortcomings in the present approach are also identified.

SECTION II
STRUCTURAL SYNTHESIS PROBLEM

1. MATHEMATICAL PROBLEM STATEMENT

The general statement for a nonlinear programming, optimum design problem can be written as follows.

$$\text{Minimize} \quad W(\bar{d}) \tag{1}$$

$$\text{Subject to} \quad g_j(\bar{d}) \leq 0 \qquad j=1,2,\ldots m \tag{2}$$

$$h_k(\bar{d}) = 0 \qquad k=1,2,\ldots p \tag{3}$$

$$d_i^{\ell} \leq d_i \leq d_i^{u} \qquad i=1,2,\ldots n \tag{4}$$

Here, $W(\bar{d})$ is the objective function and, in structural optimization problems, is typically the structural weight; $g_j(\bar{d})$ and $h_k(\bar{d})$ are the inequality and equality constraints that prescribe bounds on the response quantities of interest. The constraints are generally defined in a normalized manner as follows.

$$g_j(\bar{d}) = \frac{z(\bar{d})}{z_{all}} - 1 \leq 0 \tag{5}$$

Here, $z(\bar{d})$ is the response quantity to be constrained and, in structural design, would typically be the element stress, nodal displacement, natural frequency of the structure, or a buckling load parameter; z_{all} is the prescribed bound on this response quantity. The vector $\bar{d}$ represents the design variables that are to be optimally assigned in the optimization algorithm and are generally the element member sizes, material properties, or geometry definition parameters. The individual components d_i of the design variable vector have prescribed lower and upper bounds, d_i^{ℓ} and d_i^{u}, respectively. These permit specification of limits on design variable changes to achieve the desired objective. It is important to note that the objective and constraint functions are, for most realistic structural design problems, implicit functions of the design variables. The sensitivity of these functions for the design variables must be obtained by numerical techniques.

2. THE FEASIBLE USABLE ALGORITHM

The optimization algorithm adopted in the present work is based on the feasible directions approach of Zoutendijk (Reference 18) and is the basis of a constrained minimization program CONMIN (Reference 19). The basic approach of this technique is described herein for completeness. Consider the scalar objective function $W(\overline{d})$ that is to be minimized subject to the constraints $g_j(\overline{d}) \leq 0$, $j=1,2,...,m$, where W and g_j are general nonlinear functions of the design variables. The feasible directions approach is in the category of direct methods for constrained optimization and proceeds towards the optimum in a sequence of design variable update cycles of the form

$$d_i^{j+1} = d_i^j + \alpha^* S^j \tag{6}$$

where, S^j is the direction of search established by the algorithm and α^* is the step size that must be taken in the direction of the proposed search. The search direction is deemed to be feasible if a small move in that direction from the current design does not cause an increased violation in the constraints. For linear and convex constraints, this can be mathematically stated as

$$S^T \nabla g_j \leq 0 \tag{7}$$

where the equality condition is applicable in the case of linear and outward-curving constraints. Further, the direction is considered to be both feasible and usable, if in addition to Equation 7, the following inequality is also valid.

$$S^T \nabla F < 0 \tag{8}$$

This represents an improvement in the objective function for a minimization problem. A geometric interpretation of this approach is shown in Figure 1. The inequalities given by Equations 7 and 8 result in a feasible-usable sector in the design space in which the search must proceed. The step size selection for the algorithm is based on a one dimensional search along this direction. The basic technique used in CONMIN is to minimize W along a steepest descent direction until one of the constraint boundaries is encountered. The search then proceeds along this boundary till the objective function can

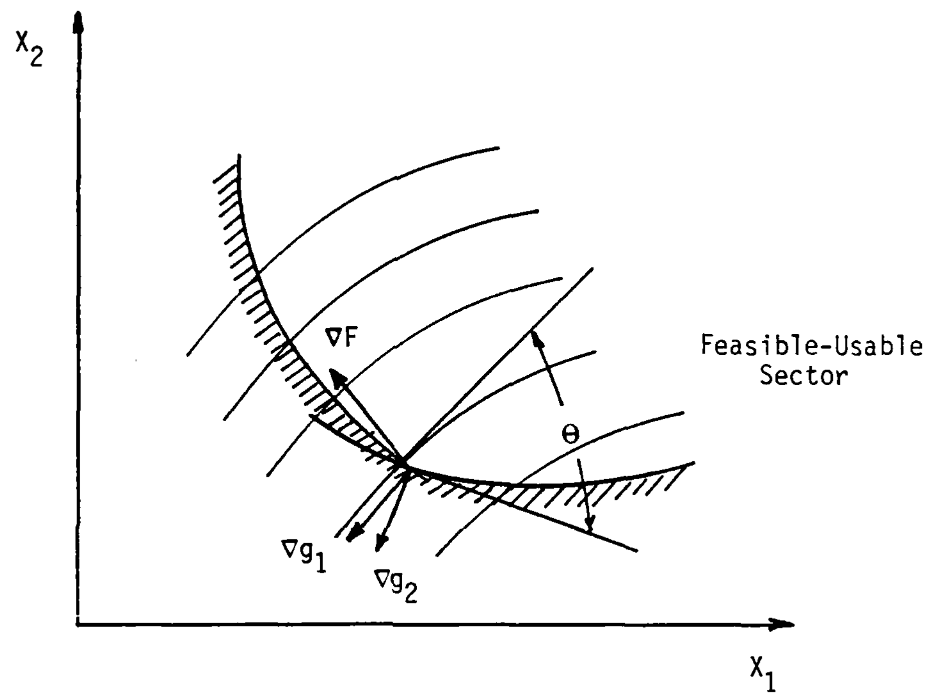

Figure 1.. Geometric Interpretation of the Feasible Usable Search Direction Approach.

no longer decrease. The significance of objective and constraint function sensitivity for the purpose of optimization is abundantly clear from this discussion.

3. HIGH VELOCITY IMPACT COMPUTATIONS - EPIC 2

The analysis for the design problem considered in this study is complex, and involves the transient dynamic response of a continuum. The ability to model arbitrary geometries of the continuum is of absolute essence in any automated design environment, and hence a discrete numerical approach is preferred. The EPIC-2 computer program is configured to obtain solutions for dynamic response analyses in impact and detonation problems, for plane strain, and axi-symmetric situations. Furthermore, it has the capability to model strain hardening and high strain rate effects that are typical of the problem under consideration. The geometry of the domain is discretized into triangular elements, with lumped masses at each node. The displacements within the elements are assumed to vary linearly between the nodes, giving the triangular elements the semblance of constant strain triangles in the finite element method. The solution grid is Lagrangian in that it moves with the material during elastic and plastic flow. For an initial set of prescribed displacements and velocities, the strains and strain rates are determined by considering the spatial derivatives of the former. The strains are then used to determine the stresses using the constitutive laws. Once the element and nodal stresses are established, the corresponding nodal forces and and nodal accelerations can also be determined. New estimates of the nodal velocity are obtained by a linear extrapolation of the velocity at the previous time step and from the acceleration determined for that step. This process is repeated for the time period of interest,and a time history of the quantities of interest such as strains, stresses, and pressures are stored for postprocessing. Additional details on the theoretical and computational aspects of EPIC-2 are available in Reference 20 .

4. EFFICIENT METHODS OF CONSTRAINT REPRESENTATION

The pressure and strain information available from EPIC-2 is a function of time and the design constraints to limit these responses to allowable

values during some predetermined initial period of impact, can be written as follows:

$$|\varepsilon_i(\overline{d},t)|/\varepsilon_{all} - 1 < 0 \tag{9}$$

$$|p_i(\overline{d},t)|/p_{all} - 1 < 0 \tag{10}$$

where, p_{all} and ε_{all} are the upper bounds on the pressure within the explosive and the strains in the structural shell, respectively. The constraints denoted by Equations 9 and 10 are parametric in time and a maximum response cannot be determined by either a close form evaluation or a functional maximization, particularly in the case of the pressure, which is a nonconvex function of time. A discrete sampling of the response is therefore used to represent the pressure and strain constraints. To avoid the problem of misrepresenting the maximum response, a large number of closely spaced points must be considered in the solution. This, coupled to the sizeable number of elements that one must include in a relatively coarse model of the structure, would result in an inordinately large number of design constraints for the problem.

This problem can be addressed by recourse to the cumulative constraint formulation which allows the user to denote a large number of design constraints by a single representative measure. For the design constraints g_j, $j=1,2,\ldots,m$, the representative cumulative constraint Ω is written as follows:

$$\Omega = \begin{cases} -\varepsilon + \sum_{j=1}^{m} \langle g_j \rangle^r & \text{if } \Omega > \phi \\ -\varepsilon + \dfrac{1}{\rho} \operatorname{Ln}\left(\sum_{j=1}^{m} \exp(\rho g_j) \right) & \text{if } \Omega < \phi \end{cases} \tag{11}$$

where $$\langle g_j \rangle = \begin{cases} g_i & \text{if } g_i > 0 \\ 0 & \text{if } g_i < 0 \end{cases}$$

where, ϕ is a preselected parameter (order 10^{-1}) that allows transition from one formulation to the other and is chosen so that the change occurs close to the constraint boundary; r is a constraint smoothing factor typically chosen as 2 but is reduced as the constraint approaches the boundary; ρ is the

constraint participation factor and its numerical value is typically of order 100. The constraint participation factor is such that the most critical constraint dominates the cumulative function. If a smaller value of ρ is chosen, a smear of a larger number of constraints can be obtained in the cumulative constraint. Discussions pertaining to the mathematical validity of the constraint representation are available in Reference 21.

SECTION III
IMPLEMENTATION OF THE PROGRAMMING SYSTEM

1. PROGRAM STRUCTURE

The analysis and optimization programs described in the preceeding sections were coupled into an automated synthesis environment by a sequence of pre- and post-processor programs. The flow between these programs and the other processors was controlled in the Command Language feature of Digital Equipment Corporation (DEC) systems, and is best illustrated in the annotated flowchart shown in Figure 2. This section of the report describes the specific tasks of each module in the flowchart, including a description of the data files that are necessary in the present implementation.

A typical input runstream for the program EPIC-2 can be broken down into three segments. The first deals with input information pertaining to the task that is to be performed, i.e., whether the program is to be run as a preprocessor only, or if dynamic response computations are required. It also contains input on what information is to be saved for postprocessing. The second portion of a typical runstream is devoted to the definition of the geometry of the problem domain,and a third segment details element connectivity information and additional information pertaining to velocity of impact and time for which response must be tabulated. In a typical synthesis procedure, it is the geometry of the structure that is generally changed to achieve the desired objectives.

The program PREEPIC is the preprocessor to EPIC-2, and is configured to generate new geometry information for the program in a desired format. It makes use of the design variables, which in the present problem are r or z coordinates of nodes, and computes the location of other node points in a grid, the order of which is predetermined and not allowed to vary. The design variable data is contained in a data file DESIGN which also contains lower and upper bounds on the design variables. Other parameters that describe the geometry of the structure, but do not change in the resizing, are contained in another data file GEOM. All data files in the present task are unformatted for ease of programming.

The optimization algorithm requires not only the function information for the pressures and strains, but also the sensitivities of these response

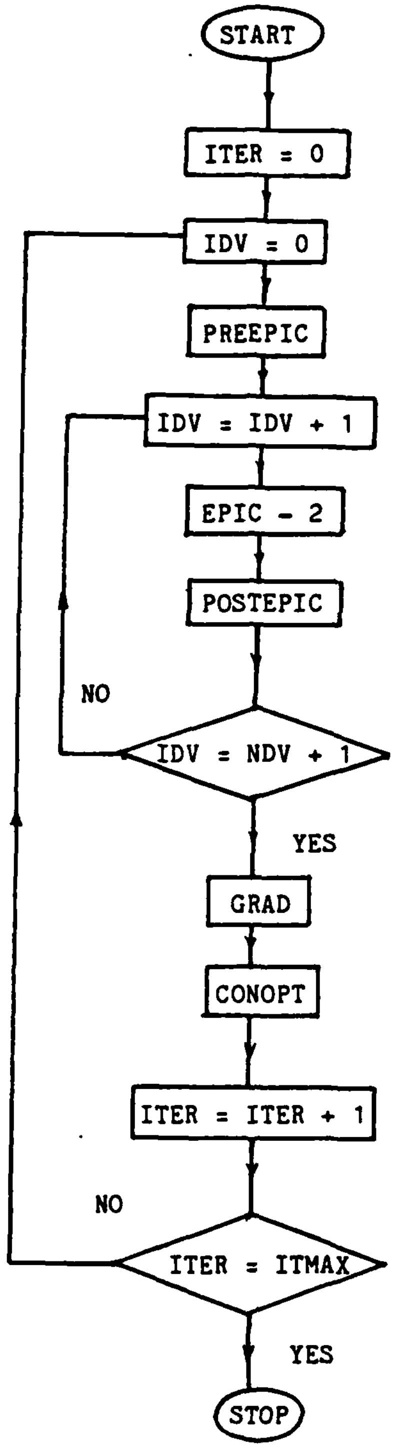

Figure 2. Flowchart for the Optimization Programming System.

quantities for each design variable. This sensitivity is obtained by a first order finite difference approximation, by perturbing each design variable, one at a time. Hence, for n design variables, the analysis to obtain the response sensitivities must be repeated n+1 times. The parameter that identifies the variable to be perturbed is in the data file NDVNCON, which also contains information on the number of design variables and constraints, the number of explosive and structural elements, and the step size for the finite difference approximation.

Each new runstream created by the preprocessor is executed by EPIC and the output information is postprocessed in the program POSTEPIC. Here, the cumulative constraints for the strain and pressure constraints are computed and stored in a data file CONFUN for computing the sensitivity information. The latter information is obtained in program GRAD and transferred to the optimization program CONOPT in a data file GGRAD. The program CONOPT contains the call to the constrained minimization program CONMIN and also provides the latter with objective function and constraint information as required. The flow chart illustrating the execution of the optimization program is shown Figure 3.

For purposes of computational efficiency, the nonlinear optimization problem was replaced by a sequence of piecewise linear approximations. Consider the case of a general nonlinear objective function $F(\overline{x})$ to be minimized subject to nonlinear inequality constraints $g_j(\overline{x})$, $j=1,2,\ldots,m$, and prescribed lower and upper bounds on the design variable vector, x_i^{ℓ} and x_i^u, respectively. At any given point in the design space, the objective and constraint functions can be assumed to be linear for small changes in the design variable vector. The function sensitivities can be obtained at the given point and updated values of the functions can be written as follows.

$$F(\overline{x} + \Delta\overline{x}) = F(\overline{x}) + \nabla F(\overline{x}).\Delta\overline{x} \tag{12}$$

$$g_j(\overline{x} + \Delta\overline{x}) = g_j(\overline{x}) + \nabla g_j(\overline{x}).\Delta\overline{x} \tag{13}$$

The validity of these approximations is ensured if the change in the design variable vector is restricted to be a small one. One possible approach of ensuring this is to permit a ±20% change in each component of the design

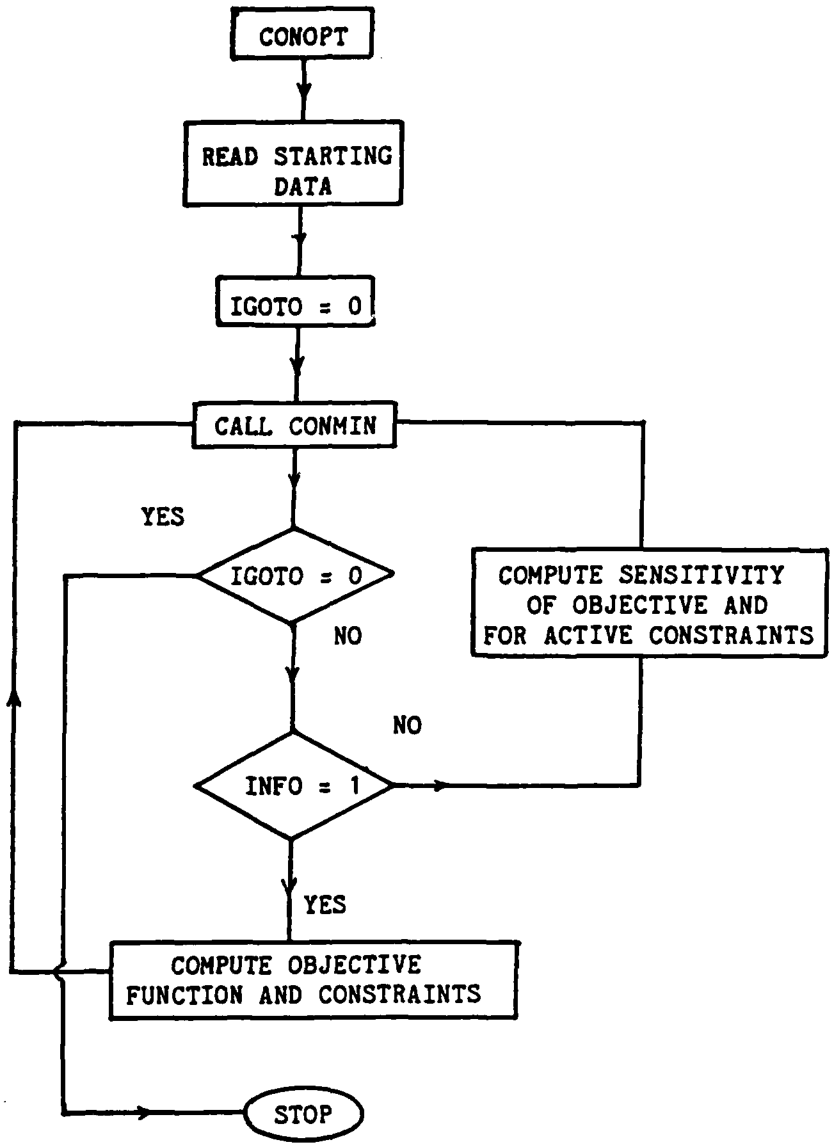

Figure 3. Flowchart for the CONMIN Optimization Algorithm.

vector for any piecewise cycle. The optimization problem statement for such a repetitive piecewise linear approximation can be stated as follows.

$$\text{Minimize} \qquad F(\overline{x}) \tag{14}$$

$$\text{Subject to} \qquad g_j(\overline{x}) < 0 \tag{15}$$

$$0.8\ x_i < x_i < 1.2\ x_i \tag{16}$$

$$x_i^{\ell} < x_i < x_i^{u} \tag{17}$$

This process is repeated till the constraints are satisfied and the objective function does not show an appreciable change in successive iterations.

2. THE TEST PROBLEM DESCRIPTION

The projectile shown in Figure 4 is chosen as a test problem to assess the validity of the programming system implemented in this study. The projectile has a steel shell and is packed with an explosive charge. It impacts a rigid target, normal to the surface and at a prescribed velocity. The rigid target assumption was made to reduce the complexity of the analysis problem as would be introduced if the projectile were allowed to penetrate the target. The impact causes severe plastic deformations to develop in the structural shell and also introduces a pressure pulse into the explosive charge. The optimum design requirements were formulated to maximize the total internal volume and hence the explosive carrying capacity of the shell. The design constraints include an upper bound on the plastic strains at any point in the shell and on the maximum pressure in the explosive. An additional constraint was imposed requiring the ratio of the explosive weight to the structural weight to be above some prespecified value.

A mathematical statement of this problem can be formulated as follows:

$$\text{Maximize } V \equiv \text{Minimize } (-V(\overline{x})) \tag{18}$$

where V is the internal volume of the shell

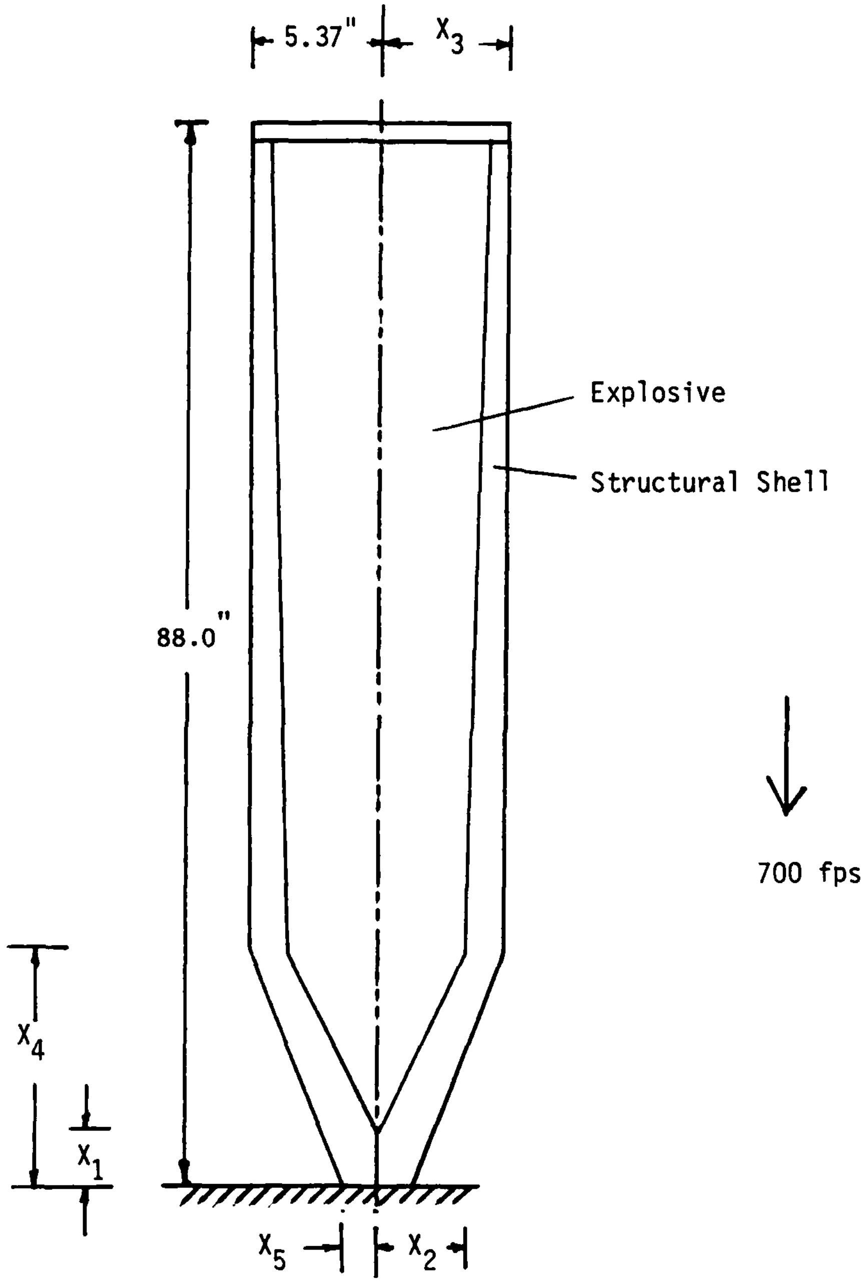

Figure 4. Projectile Undergoing High Speed Impact Against a Rigid Wall.

Subject to $g_1 \equiv \Omega_1(\varepsilon_i, \varepsilon_{all}) < 0$ (19)

$$g_2 \equiv \Omega_2(p_i, p_{all}) < 0 \quad (20)$$

$$g_3 \equiv 0.675\ W_{exp}/W_{str} - 1 < 0 \quad (21)$$

In the above expressions, the values of ε_{all} and p_{all} are 0.5 and 0.725×10^6 psi, respectively; W_{exp} and W_{str} are weights of the explosive and the structural shell. The time duration of impact for which these conditions are to be satisfied was chosen as 80 μsecs. The constant 0.675 of (21) was selected on the basis of typical explosive to structure weight ratio in a 500lb class warhead. The design variables selected for this study are designated as x_i, i=1,2,...,5, in Figure 4.

SECTION IV
NUMERICAL RESULTS

Numerical results for the problem described in the preceeding section, were obtained for two specific cases. The first, involves a fixed external geometry and variation of the first three design variables only. This permits a change in the internal geometry of the shell. To obtain a better understanding of the design space, parametric variations of the design variables were attempted to observe their influence on the strain and pressure constraints. These plots are shown in Figures 5 and 6, and show a nonlinear but monotonic behavior. A starting design variable vector of $\{x\}^T = \{2.0,4.5,4.5\}$in. was chosen. For these values of the design variables, all three constraints were violated. The internal volume of the shell was 4856.11 in^3. A total of five piecewise linear optimization cycles were required to satisfy the constraints and resulted in an optimum volume of 5715.15 in^3, and an optimum design variable vector $\{x\}^T = \{3.696,4.9,4.9\}$in. The design variables x_2 and x_3 were at their maximum permissible values at the optimum. In each piecewise linear cycle, a design variable move of ±20% was permitted. The iteration history of the objective function is shown in Figure 7.

The nose section of the projectile shows the most severe plastic deformations. A sketch of this section at time of impact and at 80 μsecs is shown in Figure 8 and the distortion is clearly in evidence. Similar plots for the optimized design with a thicker nose plate are shown in Figure 9. The extent of distortion is clearly reduced to satisfy the constraint on allowable plastic strains.

The problem was repeated with the addition of two more design variables. These were the radius of the truncated cone at the nose tip and the position of the shoulder, where the transition between the conical and cylindrical shapes occur. The starting design variable vector was the same as in the previous case, including the variables that describe the external geometry. Seven piecewise linear optimization cycles were required for convergence to an optimum volume of 5882.87 in^3, and a corresponding design variable vector $\{x\}^T = \{2.561,4.9,4.9,12.232,2.338\}$in. The nose radius increased slightly above the starting value and the shoulder of the projectile moved closer to the nose.

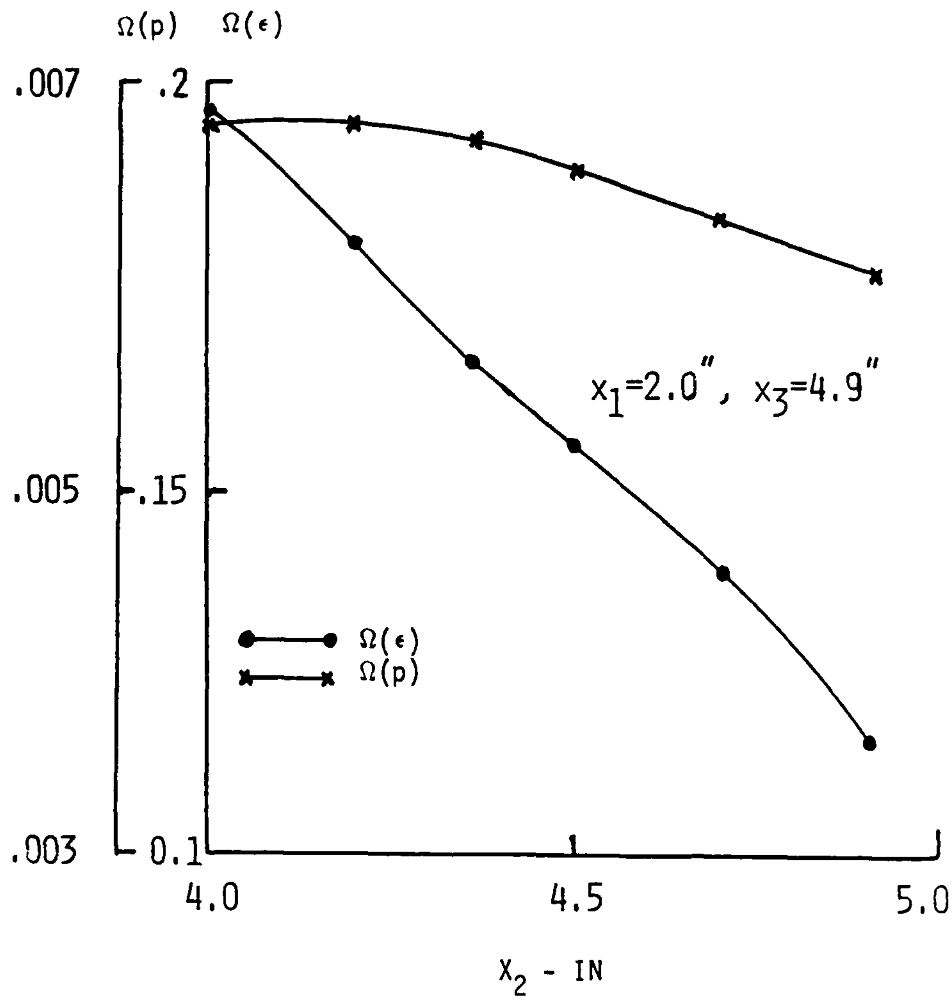

Figure 5. Effect of a Parametric Variation of Design Variables on the Strain and Pressure Constraints.

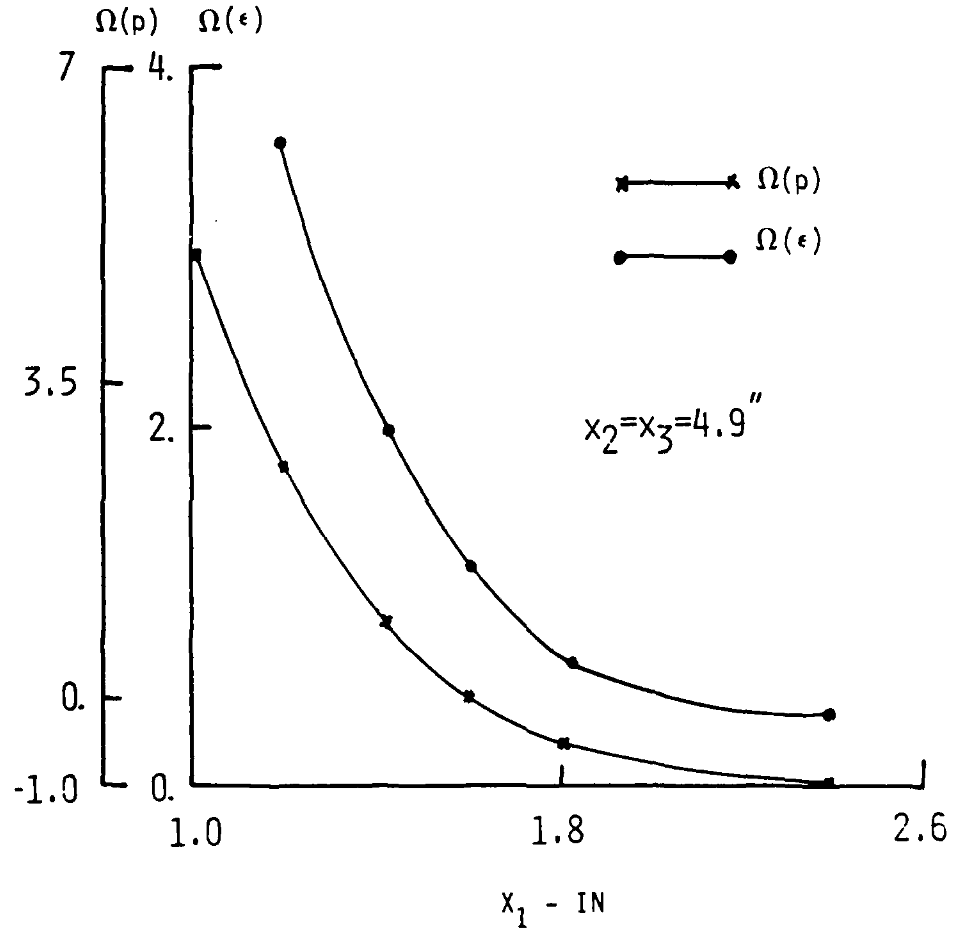

Figure 6. Effect of a Parametric Variation of Design Variables on the Strain and Pressure Constraints.

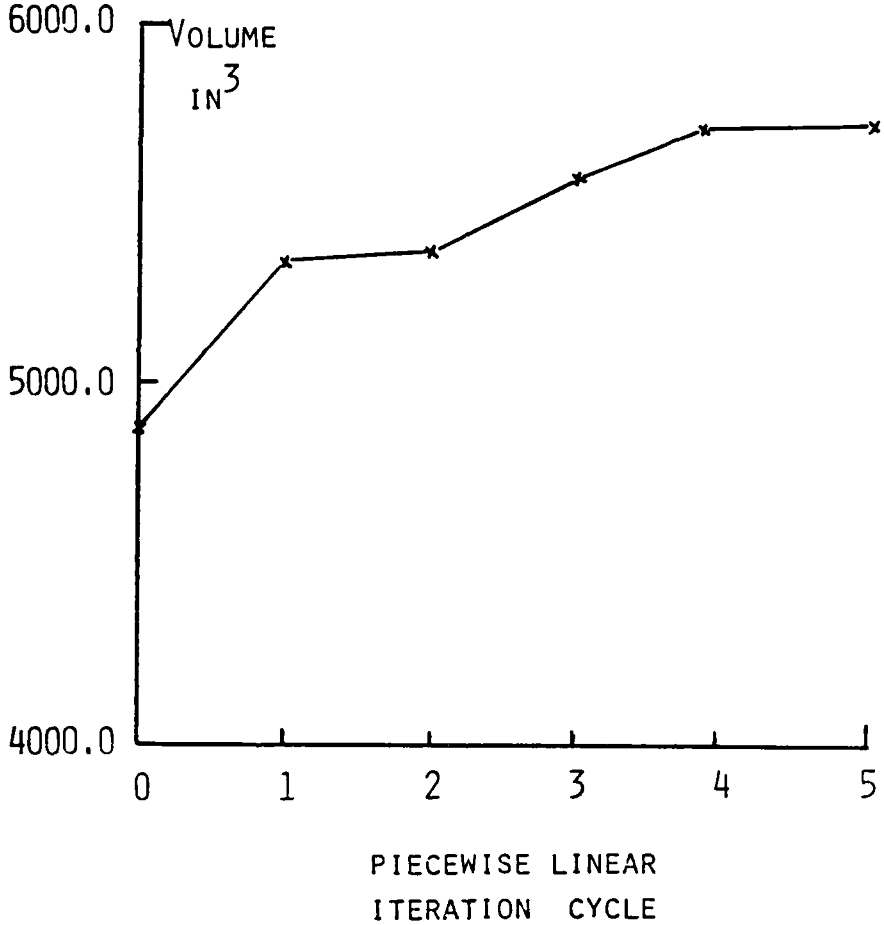

Figure 7. Iteration History for the Objective Function.

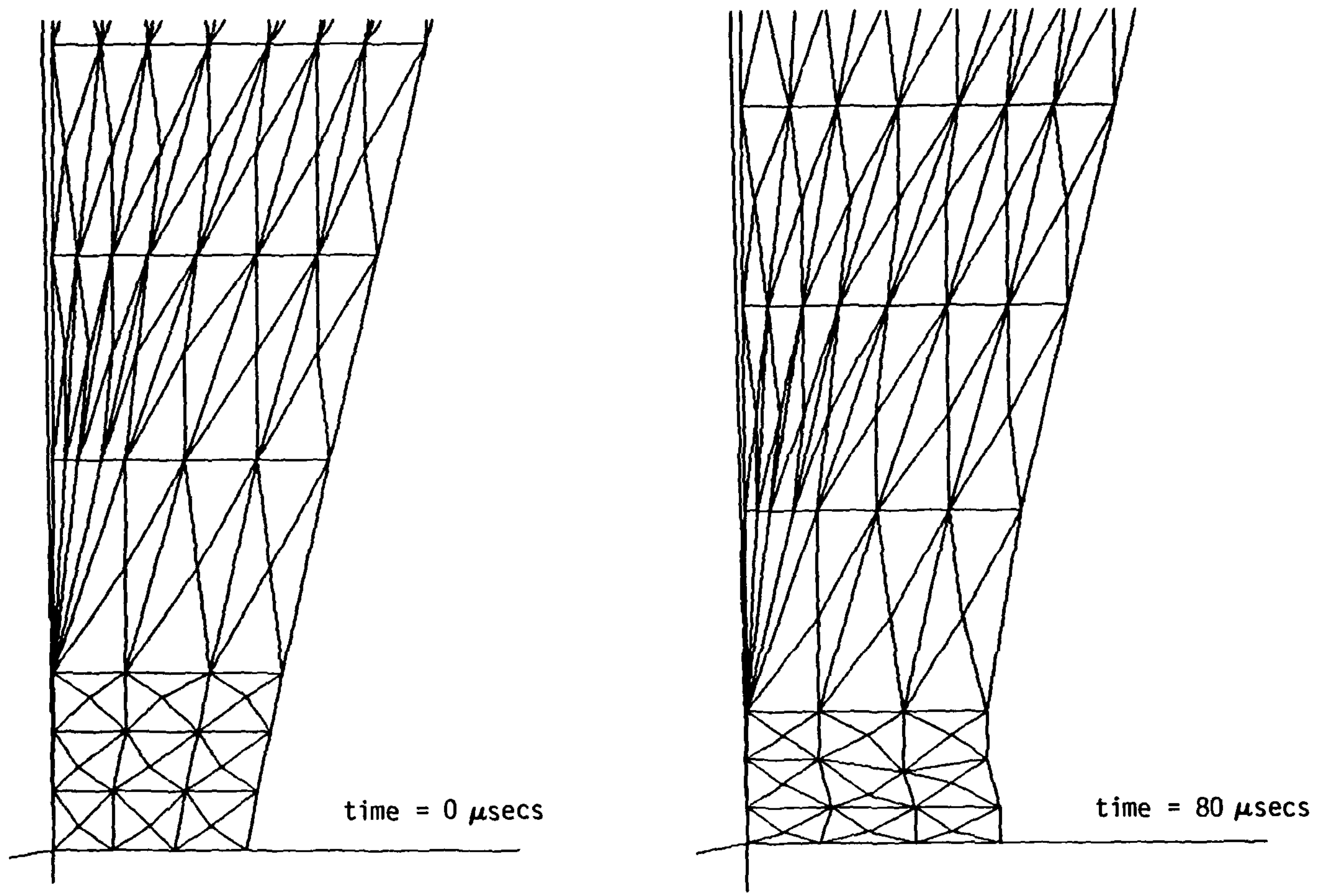

Figure 8. Initial and Final Geometry of the Nose Section of the Projectile for the Unoptimized Design.

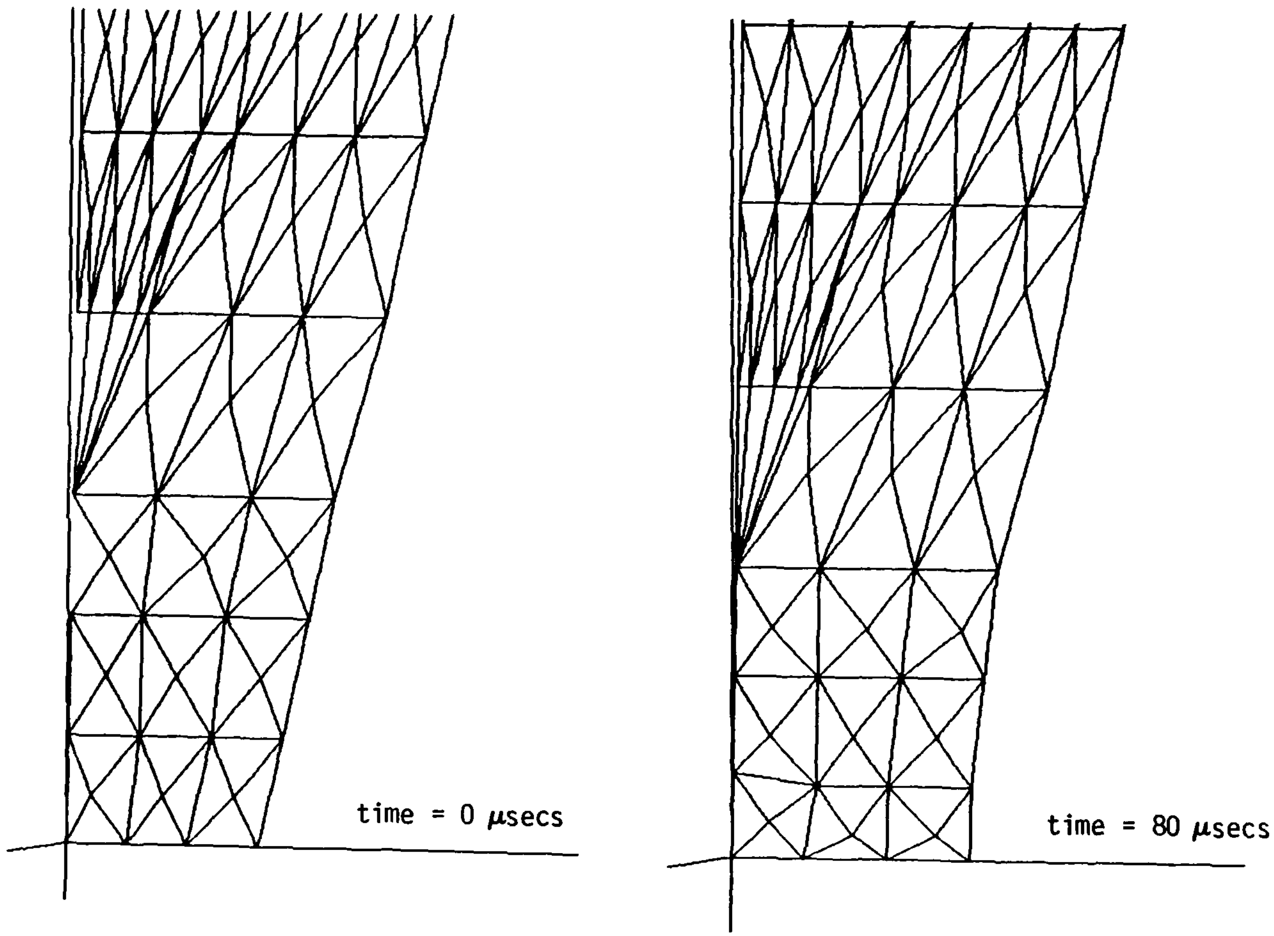

Figure 9. Initial and Final Geometry of the Nose Section of *the Projectile for the Optimized Design - 3 Design* Variables.

Plots of the strain history for the most critically strained structural element for the starting and optimized designs are shown in Figures 10a and 10b. Similar plots for the pressure response in the explosive are shown in Figures 11a and 11b. An exaggerated view of the nose section for the optimized design is shown in Figure 12. A reduction in the plastic distortion, as stipulated in the optimization requirements, is clearly indicated.

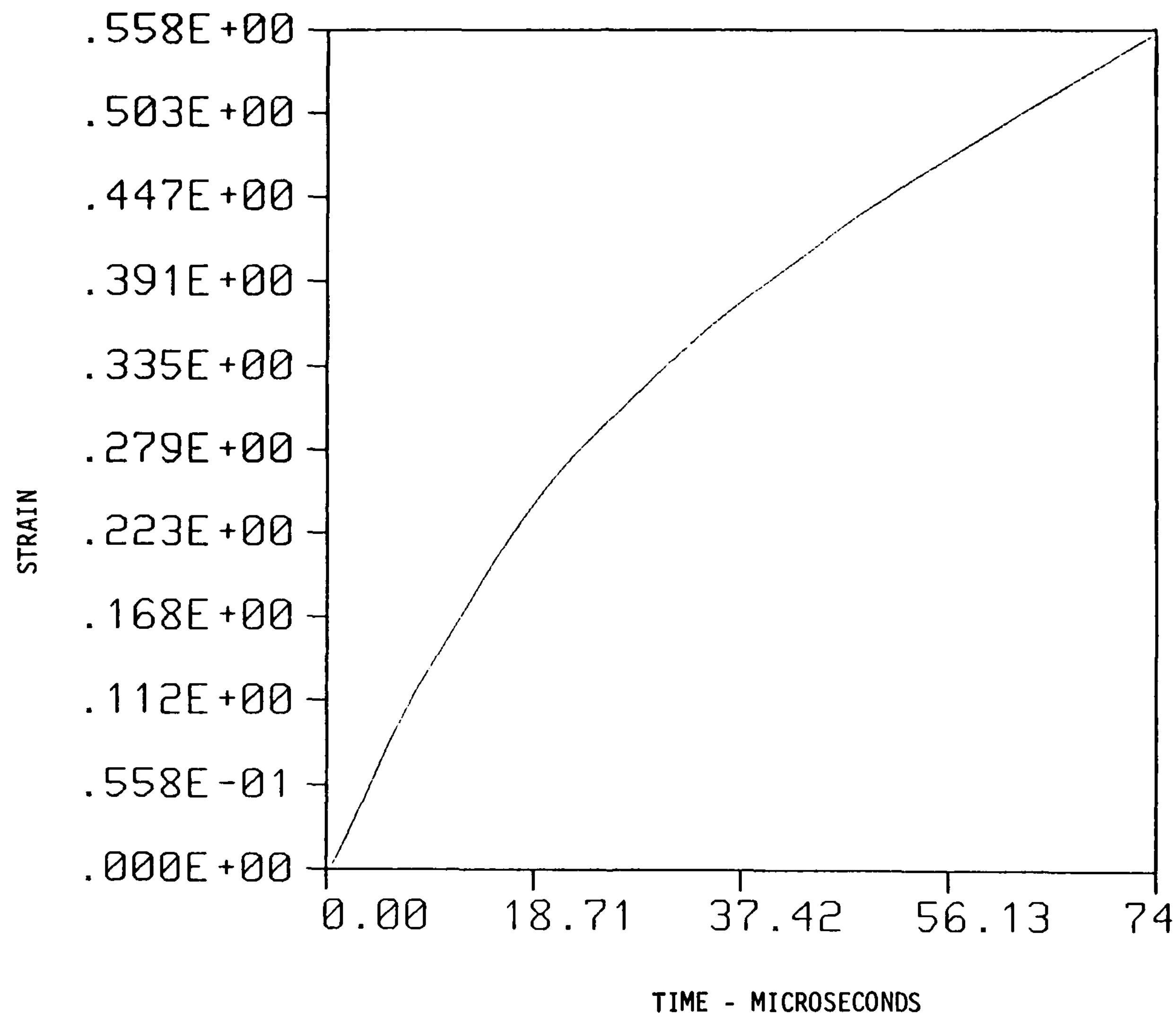

Figure 10a. Critical Element Strain History for the Unoptimized Design.

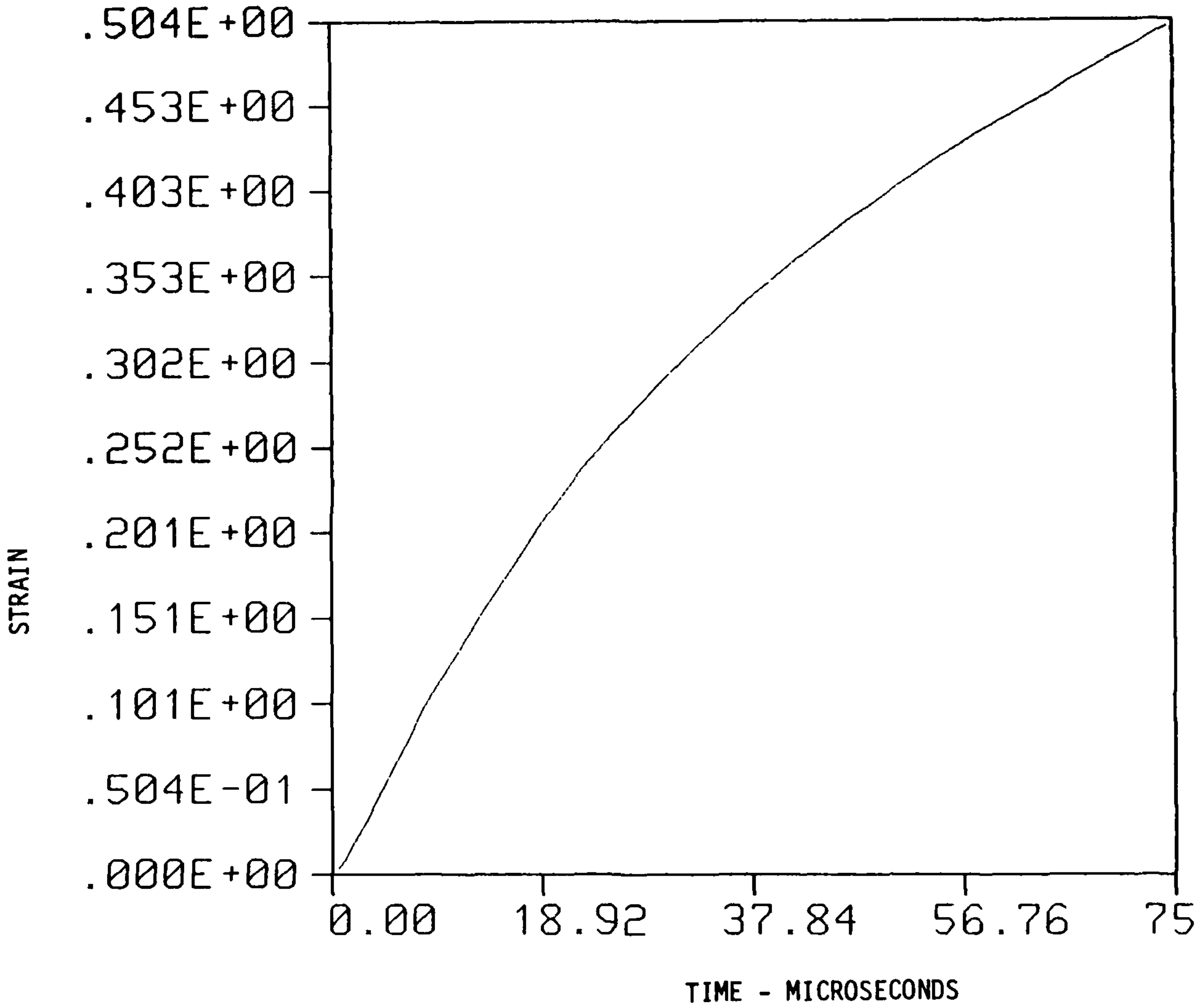

Figure 10b. Critical Element Strain History for the Optimum Design - 5 Design Variables.

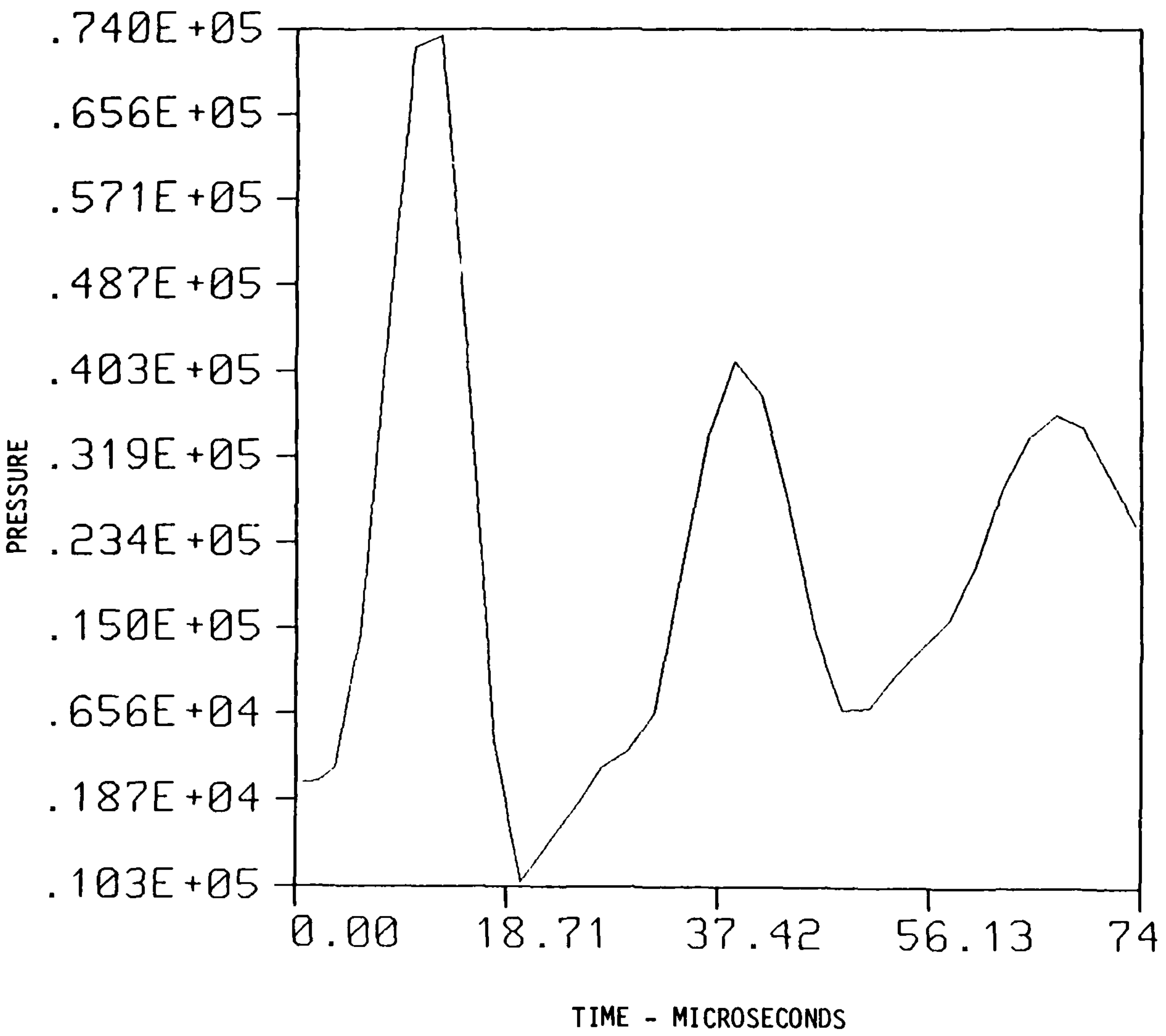

Figure 11a. Critical Element Pressure History for the Unoptimized Design.

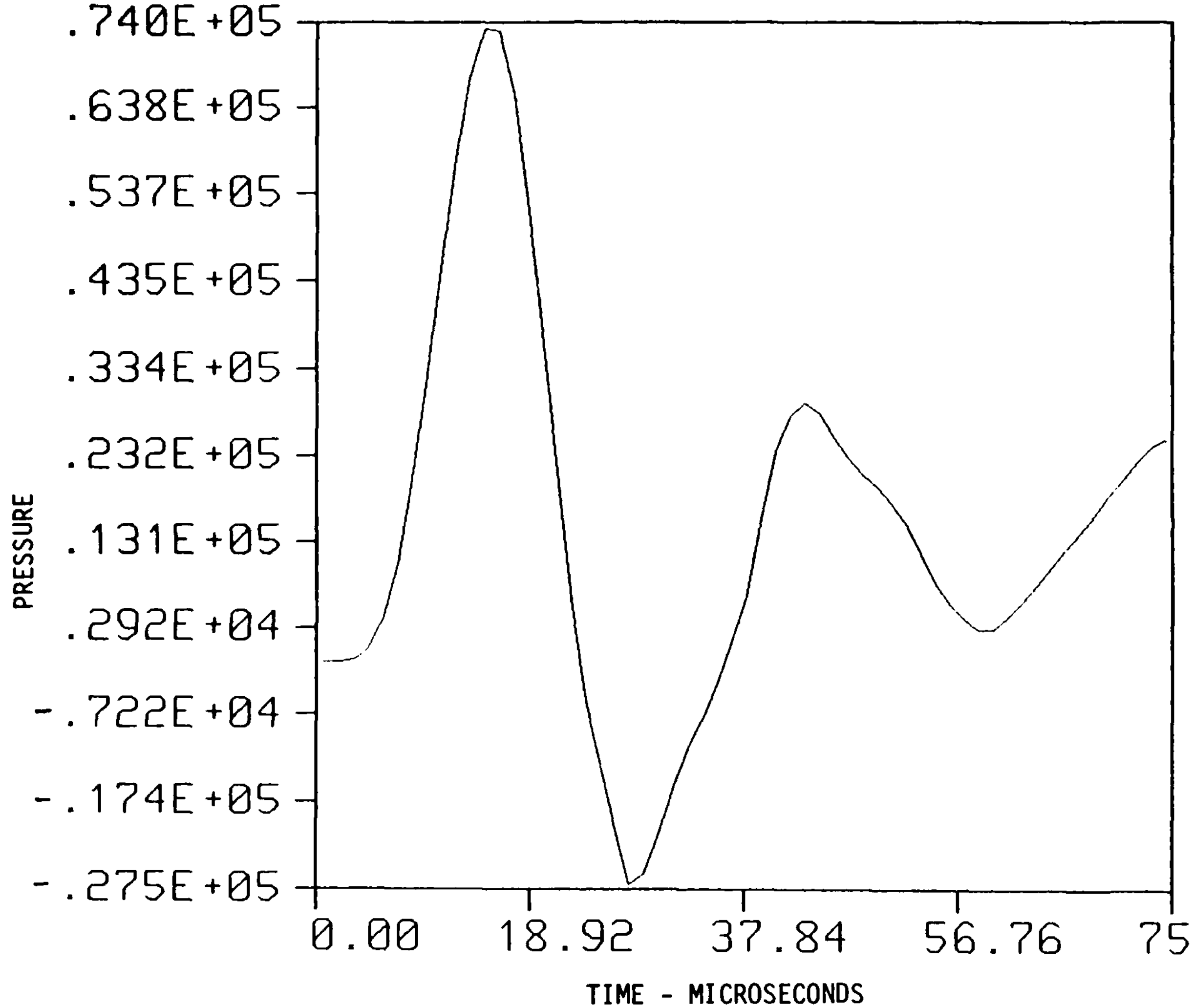

Figure 11b. Critical Element Pressure History for the Optimum Design - 5 Design Variables.

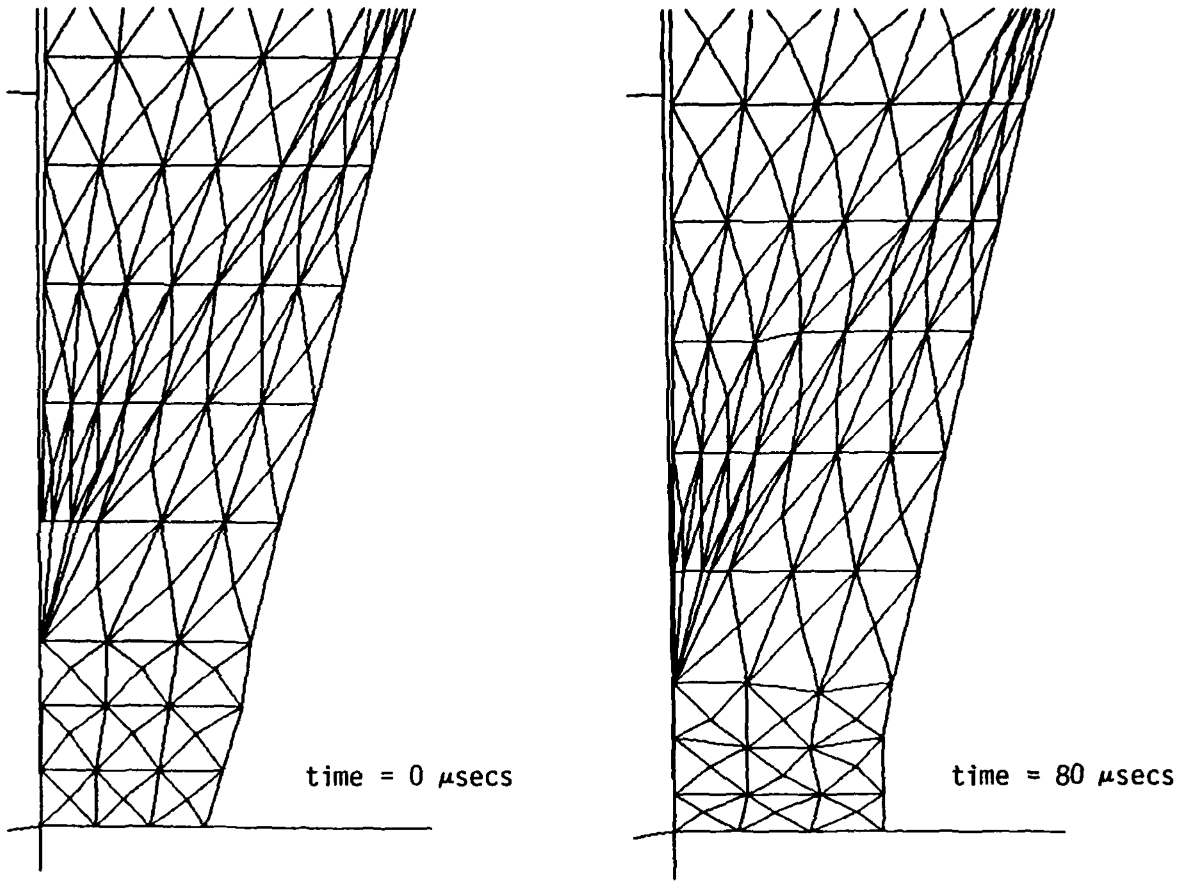

Figure 12. Initial and Final Geometry for the Nose Section of the Projectile for the Optimized Design - 5 Design Variables.

SECTION V
CONCLUDING REMARKS

The report describes the preliminary implementation of an optimum synthesis methodology for the sizing of structures that are subject to high strain rate deformations. The use of hydrocodes for analysis appears to be a logical choice for this class of problems. In the current application, the hydrocode EPIC-2 was coupled to a feasible usable search directions program CONMIN to obtain the synthesis procedure. Numerical testing of the proposed method indicates the potential for using such techniques in the design process. Extension of the current work to include target penetration and the associated time dependent pressure boundary condition on the shell, is a natural choice. Despite the encouraging results obtained in this effort, there are several issues that need to be addressed at a fundamental level.

At the very outset, it is important to emphasize the considerable investment of computational resource required for hydrocodes to run in a repetitive analysis mode. For the class of problems examined in this effort, it appears that the constraint functions can be approximated by explicit linear or quadratic functions. Approximate analysis procedures, similar to the reduced basis concepts in the synthesis of elastic structural systems, must be explored in some detail. The design problems that are most likely to be addressed in such an environment include the element of shape change in the basic configuration. This is a relatively new discipline in the field of automated synthesis and requires a focused effort in context of this problem. The response sensitivities generated by perturbing the nodal coordinate system also include the effect of a reorienting grid system. This effect must be isolated to obtain better convergence characteristics in the optimization process. The current set up is somewhat limited in that the order of the grid is not allowed to vary in the optimization. This places a restriction on the allowable changes in the design variable. A variable order, adaptable grid for the analysis problem is seen as a possible solution to this problem.

Ongoing research on this subject is expected to address some of the problems outlined above and will be reported in other publications.

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